

Biermann Mechanism in Primordial Supernova Remnant and Seed Magnetic Fields

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Abstract. We have studied the generation of magnetic fields by the Biermann mechanism in the pair-instability supernovae explosions of the first stars. The Biermann mechanism produces magnetic fields in the shocked region between the bubble and interstellar medium (ISM), even if magnetic fields are absent initially. We have performed a series of two-dimensional magnetohydrodynamic simulations with the Biermann term and estimate the amplitude and total energy of the produced magnetic fields. We find that magnetic fields with amplitude $10^{-14} - 10^{-17}$ G are generated inside the bubble, though the amount of magnetic fields generated depend on specific values of initial conditions. This corresponds to magnetic fields with total energy of $10^{28} - 10^{31}$ erg per each supernova remnant, which is strong enough to be the seed magnetic field for a galactic and/or interstellar dynamo.

Key words: magnetic fields — cosmology — interstellar medium — supernova remnant

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1. Introduction

Magnetic fields are ubiquitous in the universe. In fact, observations of rotation measure and synchrotron radiation have revealed that magnetic fields exist in astronomical objects with various scales: galaxies, clusters of galaxies, extra-cluster fields, etc. (for a review, see, e.g., Widrow 2002). The observed galactic magnetic fields have both coherent and fluctuating components whose strengths are comparable to each other (Fosalba et al. 2002; Han et al. 2004). Conventionally, these magnetic fields are considered to be amplified and maintained by a dynamo mechanism. The coherent component in a galaxy is expected to be amplified by a galactic dynamo, while the fluctuating component may be amplified by an interstellar dynamo driven by turbulent motion of the interstellar medium (ISM; Balsara et al. 2004). However, the dynamo mechanism itself cannot explain the origin of the

magnetic fields: seed magnetic fields are needed for the dynamo mechanism to work.

Thus far, various mechanisms have been suggested as a possible source of the seed field. They can be classified into two types, those of astrophysical origin and those of cosmological origin. Here we concentrate on the former (for the latter scenario, see, e.g., Davies & Widrow 2000; Takahashi et al. 2005; Amjad & Robert 2005; Tsagas 2005; Yamazaki et al. 2005). Basically, the astrophysical magnetogenesis invokes the Biermann mechanism (Biermann 1950), which is induced by the electric currents produced when the spatial gradient of the electron pressure is not parallel to that of the density. This is a pure plasma effect so that there is no need to assume unknown physics as is often done in cosmological models. Because the Biermann mechanism requires a non-parallel spatial gradient of the pressure and density, some nonadiabatic process is necessary to produce deviation from a polytropic equation of state. The strong magnetic

fields in high-redshift galaxies (Athreya et al. 1998) imply that a significant amount of the seed magnetic field should be generated at an early stage, e.g., the epoch of cosmological reionization or protogalaxy formation. For instance, Gnedin et al. (2000) studied the generation of magnetic fields in the ionizing front and found that magnetic fields as high as $\approx 10^{-18}$ G in virialized objects can be generated. Kulsrud et al. (1997) showed that a magnetic field of $\approx 10^{-21}$ G can also be generated at shocks of large-scale structure formation.

In this paper, we investigate magnetogenesis at smaller scales. Specifically, we study the amplitude of the magnetic field produced by the Biermann mechanism when the shock waves of the supernova explosions of the first stars are spreading throughout the ISM (Hanayama et al. 2005). The primordial supernova explosions are expected to take place effectively, since the initial mass function (IMF) of Population III stars should be substantially top-heavy (e.g., Abel et al. 2002). We perform a series of two-dimensional magnetohydrodynamic (MHD) numerical simulations in which the Biermann term is included. We also discuss whether they can be the origin of the cosmic magnetic fields. Consequently, we find that the spatially averaged amplitude of the produced magnetic field in virialized objects reaches $\sim 10^{-16}$ G, which is much greater than those expected from cosmic reionization and large-scale structure formation. Thus, the supernova explosions of the first stars can be effective sources for the seed magnetic fields. Although the situation considered here is somewhat similar to that of Miranda et al. (1998), they assumed a multiple-explosion scenario of structure formation and considered explosions of objects with mass $> 10^6 M_\odot$ at $z \geq 100$, which is clearly unrealistic in the context of the current standard model of structure formation.

2. Numerical simulations and results

We solve the two-dimensional MHD equations using conserved quantities with heating and cooling adjusted for the ISM. The induction equation with Biermann term is as follows:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \alpha \frac{\nabla \rho \times \nabla P}{\rho^2} \quad (1)$$

where ρ , \mathbf{v} , P , and \mathbf{B} are the density, velocity, pressure, and magnetic field, respectively. The last term of the right-hand side of equation (1) is the Biermann term: α in equation (1) is the so-called Biermann coupling constant defined by $\alpha = m_p c / e(1 + \chi) \sim 10^{-4}$ G s, where m_p , e , and χ are the proton mass, electric charge, and ionization fraction, respectively. Although the gas temperature just before star formation begins is rather cool ($T \sim 200$ K; Abel et al. 2002; Bromm et al. 2003; Omukai & Palla 2003), UV radiation from the first stars ionizes the surrounding ISM (Freyer et al. 2003; Mori et al. 2004). Thus we set $\chi = 5/6$ assuming $n_{He}/n_H \sim 0.1$. We use a cooling function derived by Raymond et al. (1976). When parcels cool below 10^4 K, an artificial heating rate proportional to the density is used. The constant heating coefficient is set so that heating balances cooling at the ambient density and temperature. Although the cooling function and heating rate in the primordial gas are not clear so

far, they are not important for the adiabatic expansion phase that we concentrate on.

We solve the above equations by the two-dimensional MHD code in cylindrical coordinates (r, z, ϕ) assuming axial symmetry around the symmetry axis (z). The code is based on the modified Lax-Wendroff scheme with an artificial viscosity of von Neumann and Richtmyer to capture shocks. The numerical scheme was tested by comparing known solutions that have been obtained either analytically and numerically (see e.g., Hanayama & Tomisaka 2005).

In all the computations, grid spacings are chosen $\Delta r = \Delta z = 0.1$ pc. For example, the numerical domain covers a region of $130 \text{ pc} \times 130 \text{ pc}$ with $1300 (r) \times 1300 (z)$ mesh points in our fiducial model. We begin the simulation by adding a thermal energy of $E_0 = 10^{53}$ or 10^{52} erg within the sphere of 2 pc in radius.

As the bubble expands, the ejected gas interacts with the ISM, and a shock wave is formed. In the shocked region the gas is heated nonadiabatically, which is a necessary condition for the Biermann mechanism to work. Here the structure of the interstellar environment is important because it affects the density and pressure profiles of the shocked region that is directly related to the Biermann term. We assume an inhomogeneous ISM with average density $n_{\text{ISM}} = 0.2 \text{ cm}^{-3}$. This is roughly consistent with the situation discussed in Bromm et al. (2003). The scale length of the density and the amplitude of the inhomogeneity are as yet poorly understood, and we assume inhomogeneity with the scale length $\lambda = 1$ pc and density variation $0.2 \times 2^{\pm 1} \text{ cm}^{-3}$, which are values similar to those in our galaxy. Within the variation, the amplitude of the density is given at random and the distribution is smoothed numerically to create a perturbation. This is our fiducial model for the ISM. As we show in the next section, the amplitude of the produced magnetic field is sensitive to the scale length λ , while the average density and the amplitude of the density variation are rather unimportant. Thus we consider several different models in addition to the fiducial model: specifically, we vary the mean density [$1 \times 2^{\pm 1} \text{ cm}^{-3}$ and $10 \times 2^{\pm 1} \text{ cm}^{-3}$] and the scale length (3 and 10 pc).

As for the explosion energy of the supernova, we adopt $E_{\text{SN}} = 10^{53}$ erg for the fiducial model. This explosion energy corresponds to stars with mass $250 M_\odot$ that explode as a pair-instability supernova (Fryer et al. 2001). In addition, we consider a model with $E_{\text{SN}} = 10^{52}$ erg as a variation.

Figure 1 shows the contours of the gas density and the amplitude of the magnetic field produced by the end of the adiabatic expansion phase $t = 1.26 \times 10^5$ yr for the fiducial model. The radius of the bubble is about 125 pc, and turbulent motion is induced in the shocked region because of the inhomogeneity of the ISM. The amplitude of the magnetic field is about 10^{-14} G for the central region and about 10^{-17} G just behind the shock. The total magnetic energy inside the bubble is about 10^{30} erg.

We have also checked the case of a homogeneous medium to test the robustness of our computation. We find that, on average, a SNR generates magnetic fields with an amplitude $\sim 10^{-19}$ G behind the shock front, which is $\sim 10^{-3}$ times smaller than that in an inhomogeneous medium. Therefore, in

the case of a homogeneous medium, we estimate a numerical error of the amplitude of the magnetic field of $\sim 10^{-19}$ G. It should be noted that the resulting magnetic field has only a toroidal component because axial symmetry was assumed.

In Figure 2, we show the time evolution of the total magnetic energy for various models. The behaviors are qualitatively similar for all the models. The robust knees around 10^3 yr in Figure 2 come from the formation of an adiabatic shock front: this corresponds to when the SNR shifts from the free expansion phase to the Sedov phase. The total magnetic energy at the end of the adiabatic expansion phase is larger for models with a smaller scale length of the ISM density. This tendency is confirmed by an order-of-magnitude estimate in the next section. For models with large average ISM density or small explosion energy, the total magnetic energy is smaller because the bubble is smaller than in the other models. Although there are many uncertainties in the initial conditions, the generation of a magnetic field with a total energy of $10^{28} - 10^{31}$ erg appears to be robust.

3. Analytic estimates of magnetic fields and implications for the seed magnetic field

To understand the result of the numerical simulations, in this section we perform an order-of-magnitude estimation of the strength of the magnetic field produced by the Biermann mechanism. The amplitude of the magnetic field produced by the Biermann mechanism can be estimated from the Biermann term in equation (1),

$$B_{\text{Biermann}} \sim \alpha \frac{\nabla \rho \times \nabla P}{\rho^2} \Delta t, \quad (2)$$

where $\Delta t \sim 10^3$ yr is the characteristic timescale in which the Biermann mechanism works. Taking the characteristic pressure to be the ram pressure of the gas, $P \sim P_{\text{ram}} = \rho v_{\text{bub}}^2$, and the characteristic velocity of the bubble $v_{\text{bub}} \sim 10^{-3}$ pc yr $^{-1}$, we obtain

$$\begin{aligned} B_{\text{Biermann}} &\sim \alpha \frac{v_{\text{bub}}^2}{\lambda L} \Delta t \\ &\sim 3 \times 10^{-15} \left(\frac{v_{\text{bub}}}{10^{-3} \text{ pc yr}^{-1}} \right)^2 \left(\frac{\lambda}{1 \text{ pc}} \right)^{-1} \\ &\quad \times \left(\frac{L}{1 \text{ pc}} \right)^{-1} \left(\frac{\Delta t}{10^3 \text{ yr}} \right) \text{ G}, \end{aligned} \quad (3)$$

where L is the scale length of the pressure component perpendicular to the density gradient. Then the magnetic energy produced by the Biermann mechanism for each primordial SNR can be estimated as

$$\begin{aligned} E_B &\sim \frac{4\pi R_{\text{bub}}^3}{3} \frac{B_{\text{Biermann}}^2}{8\pi} \\ &\sim 5 \times 10^{31} \left(\frac{R_{\text{bub}}}{100 \text{ pc}} \right)^3 \left(\frac{v_{\text{bub}}}{10^{-3} \text{ pc yr}^{-1}} \right)^4 \left(\frac{\lambda}{1 \text{ pc}} \right)^{-2} \\ &\quad \times \left(\frac{L}{1 \text{ pc}} \right)^{-2} \left(\frac{\Delta t}{10^3 \text{ yr}} \right)^2 \text{ erg}, \end{aligned} \quad (4)$$

which is consistent with the value obtained from our numerical simulations.

The dependence of the total magnetic energy on several parameters can also be understood from equation (4). It is found directly from equation (4) that $E_B \propto \lambda^{-2}$. To examine the dependence on the other parameters, we simply assume the Sedov-Taylor solution:

$$R_{\text{bub}} \propto t^{2/5} \left(\frac{E_{\text{SN}}}{n_{\text{ISM}}} \right)^{1/5}, \quad v_{\text{bub}} \propto t^{-3/5} \left(\frac{E_{\text{SN}}}{n_{\text{ISM}}} \right)^{1/5}. \quad (5)$$

Putting these into equation (4) yields $E_B \propto (E_{\text{SN}}/n_{\text{ISM}})^{7/5}$. Our numerical results shown in Figure 2 are quite consistent with these simple estimations.

Now we estimate the spatially averaged energy density of the magnetic fields produced by the first stars and consider whether they can be a source of the seed fields. For the primordial star formation rate, we extrapolate the one by Pelló et al.(2004) and Ricotti et al.(2004); $\dot{\rho}_* \sim 10^{-2} M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$. Denoting the magnetic energy produced by the Biermann mechanism as $\epsilon_{\text{SN}} \sim 10^{30}$ erg, the magnetic energy density produced during the formation period of the first-star ($\tau \sim 1$ Gyr) can be obtained as

$$\begin{aligned} e_B &\sim f_{\gamma\gamma} \dot{\rho}_* \left(\frac{\epsilon_{\text{SN}}}{M_{\text{SN}}} \right) \tau \\ &\sim 10^{-40} \left(\frac{f_{\gamma\gamma}}{0.06} \right) \left(\frac{\dot{\rho}_*}{10^{-2} M_{\odot} \text{ yr}^{-1}} \right) \left(\frac{M_{\text{SN}}}{250 M_{\odot}} \right)^{-1} \\ &\quad \times \left(\frac{\epsilon_{\text{SN}}}{10^{30} \text{ erg}} \right) \left(\frac{\tau}{1 \text{ Gyr}} \right) \text{ erg cm}^{-3}, \end{aligned} \quad (6)$$

where M_{SN} is the typical mass scale of first stars that end up in pair-instability supernovae, and $f_{\gamma\gamma}$ is the mass fraction of such first stars; we adopt $f_{\gamma\gamma} = 0.06$, which was derived under the assumption that very massive black holes produced from the first stars end up in supermassive black holes in galactic centers (Schneider et al. 2002). We note that the value is the comoving density averaged in the universe; we can convert the value to physical density in virialized objects (i.e., protogalaxies) as

$$\begin{aligned} e_{B,\text{gal}} &\sim e_B (1+z)^4 \Delta \sim 10^{-34} \left(\frac{e_B}{10^{-40} \text{ erg cm}^{-3}} \right) \\ &\quad \times \left(\frac{1+z}{10} \right)^4 \left(\frac{\Delta}{200} \right) \text{ erg cm}^{-3}, \end{aligned} \quad (7)$$

where Δ is the density contrast. This corresponds to the mean magnetic field of $B \sim 10^{-16}$ G in protogalaxies, which is much stronger than that expected in ionizing fronts, $B \sim 10^{-18}$ G (Gnedin et al. 2000).

4. Summary and discussion

We have studied the generation of magnetic fields in primordial supernova remnants. We have performed two-dimensional MHD simulations with the Biermann term, which can produce a magnetic field through the nonadiabatic interaction between the bubble and ISM, even if there is no magnetic field at first. We have found that the ISM around the primordial supernovae is an effective site for producing magnetic fields. The total energy of the magnetic fields is $10^{28} - 10^{31}$ erg, depending on the parameters adopted. On

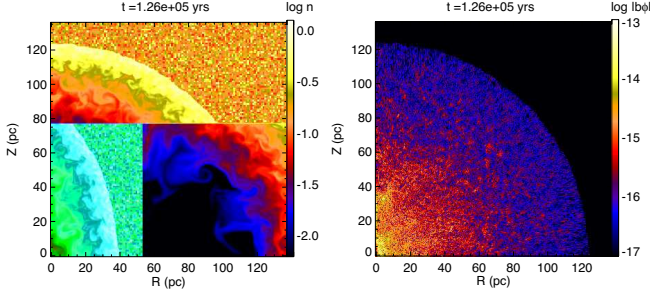


Fig. 1. Contours of the gas density (*left*) and the magnetic field (*right*) at the end of the adiabatic expansion phase ($t = 1.26 \times 10^5$ yr) for the fiducial model. The amplitude of the magnetic field is about 10^{-14} G at the central region and about 10^{-17} G just behind the shock.

the basis of the results, we have estimated the spatially averaged energy density of the magnetic fields produced by the first stars during the formation period of the first stars. The averaged energy density is about 10^{-40} erg cm $^{-3}$, which corresponds to $B \sim 10^{-16}$ G in protogalaxies at $z \sim 10$. This is much greater than expected from cosmic reionization and large-scale structure formation. Thus primordial supernova remnants would be a promising source for the seed fields for the galactic and/or interstellar dynamo.

Although the coherence length of the seed field computed here is much smaller than the galactic scale, it can be amplified by the galactic dynamo to produce a coherent component if the coherence length is about 100 pc (Poezd et al. 1993; Ferrière & Schmitt 2000), which is a typical size of supernova remnants. It might also be amplified by an interstellar dynamo to produce the fluctuating component (Balsara et al. 2004). While it is beyond our scope to discuss the relation between the magnetic field produced and the galactic/interstellar dynamo, we plan to investigate the evolutions of the seed magnetic fields computed here as a result of the dynamo processes on the large scale of galaxies and clusters of galaxies. This will be presented in a forthcoming paper (H. Hanayama et al. 2005, in preparation).

Regarding their use as an observational signature, a proposal to detect seed magnetic fields was made by, e.g., Plaga (1995). If there exist intergalactic magnetic fields produced by the primordial SNRs, the arrival time of high energy gamma-ray photons from extragalactic sources would be delayed by the action of intergalactic magnetic fields on electron cascades (Ando 2004). Even a magnetic field as weak as $\sim 10^{-24}$ G would be detectable if the delay of the arrival time comes within a reasonable range (a few days). Therefore the mechanism of magnetic field generation proposed in this paper might be tested by the future high-energy gamma-ray experiments such as *GLAST* (*Gamma-Ray Large Area Space Telescope*).

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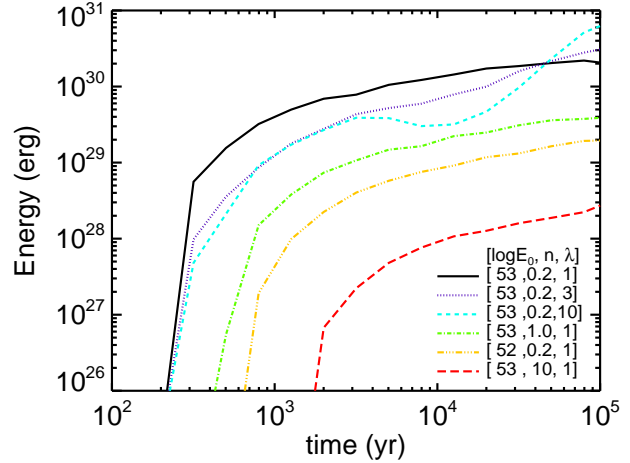


Fig. 2. Time evolution of the total magnetic energy produced by the Biermann mechanism for various models.

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